

SWITCH DEVELOPMENT AT CEM-UT

D. R. Peterson, R. C. Zowarka and B. M. Rech
Center for Electromechanics
The University of Texas at Austin
Austin, TX 78712

Summary

Two reusable (with replacement of a few expendable components), fast (tens of microseconds), megampere switches operated with commercially available explosive charges suitable for indoor laboratories are described. One is a low-inductance, triggerable opening switch and the other, a metal-to-metal self-assisted closing switch.

The opening switch is the second stage of a two-stage switch for storage inductor commutation. The first stage is a heavy-duty mechanical switch. The explosive switch itself has a number of stages in series which can be fired simultaneously, for high voltage, or sequentially for millisecond pulses into loads of time-increasing impedance (electric guns).

The closing switch is actuated by projection of a metal ring into the tapered gap between coaxial electrodes. The switch is simple, self-contained, readily scaled to larger sizes, and fast enough for crowbarring electric guns. Large ring mass (>100 g) enables heavy-duty uses such as crowbarring homopolar generators.

Introduction

Homopolar generators convert megajoules of kinetic energy stored in a rotating armature into megampere current pulses, but at low voltages (50 V). If the homopolar pulse is delivered to an energy storage inductor, higher voltages (thousands of volts) may be produced when the inductor is commutated into an appropriate load. A variety of applications await the maturation of opening switch technology to accomplish this commutation. The problem of opening switches to commutate large current has recently been reviewed by Honig.¹

The prototype application of homopolar charged inductors is the railgun. The first successful demonstration of a homopolar powered, high velocity railgun was accomplished by Rashleigh and Marshall.² More recent work is described in references 3 to 6. This paper describes several switches under development or in use in the CEM-UT laboratory.

The parameters of the 6-MJ compact homopolar generator and cryogenic (liquid nitrogen) storage inductor^{7,8} are summarized in Table 1. The generator is equipped with a two-stage switch which is currently undergoing testing. The first stage switch is a heavy-duty mechanical switch, which is capable of carrying the homopolar current, as the inductor is being charged. When charging is complete, the mechanical switch commutates the current into the explosive switch. The final commutation is accomplished by firing the explosive switch as shown schematically in Figure 1. The two-stage arrangement is used because the mechanical switch, although capable of carrying the current for the long charging time, develops insufficient commutation voltage to switch the current into the load fast enough. The explosive switch develops higher commutation voltage, but is not substan-

Table 1. Summary of the parameters of the 6-MJ compact homopolar generator and cryogenic storage inductor

Homopolar Generator

Maximum kinetic energy	6.2 MJ
Maximum armature current	1.0 MA
Maximum open circuit voltage	50 V
Internal resistance	6 $\mu\Omega$

Storage Inductor

Inductance (4 turn)	3.8 μH
Inductance (5 turn)	6.0 μH
Cold resistance	5.3 $\mu\Omega$
Warm resistance	22 $\mu\Omega$
Maximum stored inductive energy	3.1 MJ

Overall system mass	3,200 kg
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tial enough to carry the current for the duration of the charging cycle.

The explosive second stage has the advantage of being triggerable. The explosive switch can be fired on demand anytime after completion of the current commutation from the mechanical switch into the explosive switch. Thus, the two-stage switch lends itself to applications requiring precision timing, e.g. powering a railgun in which the projectile is injected into the breech by a gas-powered gun. The heavy-duty opening switch, the explosive opening switch, and an explosive closing switch are described in more detail below.

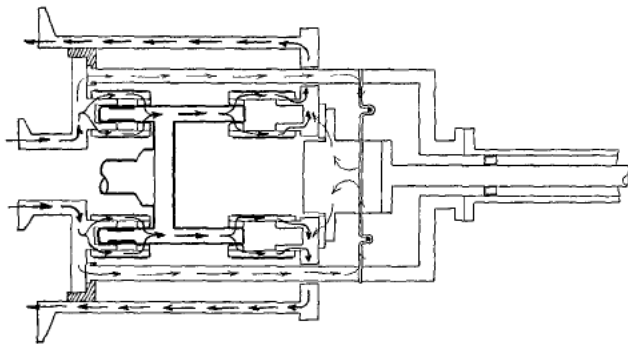
Mechanical Switch

The mechanical switch is of a coaxial geometry. Brushes to effect the commutation contact the moveable center conductor which is driven by high-pressure nitrogen delivered through a burst diaphragm punctured by a solenoid-activated lance. The commutation voltage is developed by arcs drawn as the brushes move from copper onto a sprayed ceramic insulator. The mechanical switch generates 30 V to commutate the current into the explosive second stage, which presents an inductance of 46 nH, in 600 μs . Mechanical damage to the armature accumulated during 20 200-kA commutations is shown in Figure 2.

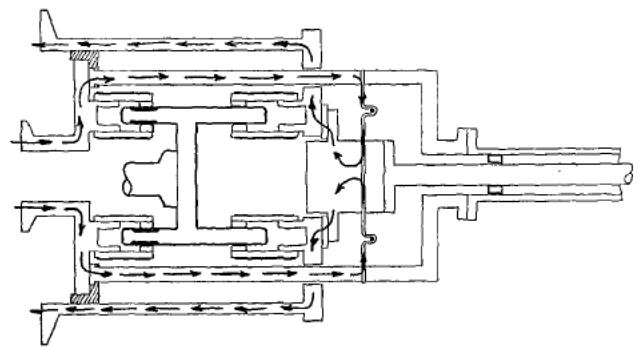
Explosive Opening Switch

The explosive second stage of the two stage switch, is of the variety developed by Ford and Vitkovitsky.⁹ Although the switch must be reloaded for each use, it is extremely simple and versatile. The explosive charge is 3.2 g/m (15 grains per foot) commercial detonating cord. The total charge required to operate the switch is small enough (2 to 6 g) that the switch may be used in indoor laboratories. All of

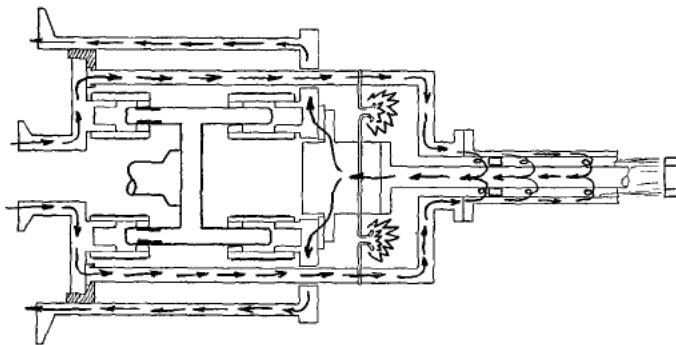
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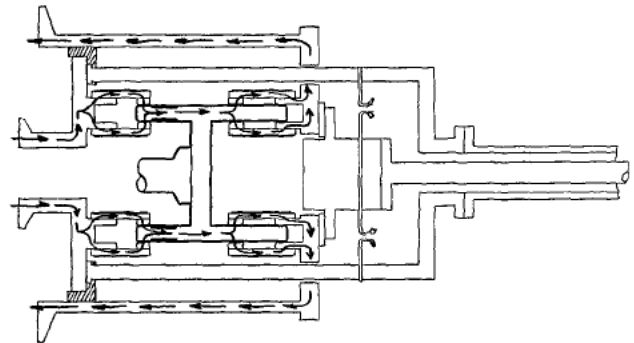
A OPENING SWITCH CHARGING PATH



B OPENING SWITCH COMMUTATION PATH



C OPENING SWITCH COMMUTATION INTO RAILGUN LOAD



D OPENING SWITCH REMAKING TO CROWBAR POWER SUPPLY

Figure 1. The commutation cycle

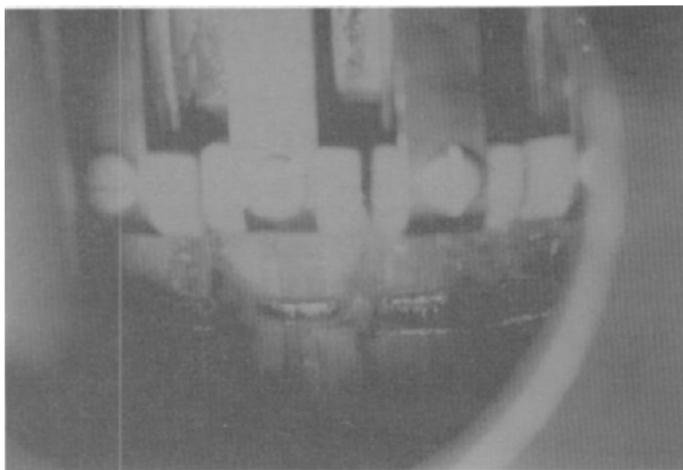


Figure 2. Mechanical damage to the armature

the switch components are reusable except the expendable aluminum switching element.

The switch operates by the explosive removal of a section of thin aluminum bus. The commutation voltage is developed in arcs drawn as the metal parts. In its present configuration, the switch has four parallel branches, 15-cm wide and 0.8-mm thick. Each of the branches can be equipped with one, two, or three series explosive elements. The series elements can be

detonated simultaneously for maximum commutation voltage or sequentially to enable the switch to withstand high load voltages for maximum time. Figure 3 shows the explosive switch and mechanical switch mounted on the cryogenic inductor for a test to commute the current into a dummy load.

The performance of the switch has been tested by commutating a 480-kA current delivered by a capacitor-charged 0.7- μ H inductor. The results of the tests are summarized in Table 2. Commutation time into the 50-nH load was 10 μ s or less.

Table 2. Summary of explosive opening switch test results

Test	Load	Peak commutation voltage	Number of series switch elements detonated simultaneously
1	open circuit	> 2	1
2	50 nH	0.8	1
3	50 nH	1.3	2
4	50 nH	1.5	3

In the open circuit test, the opening of the switch resulted in the explosive dissipation of electrical energy. This electrical explosion was triggered by only 12 kJ of chemical energy. In the tests commutating the current into a 50-nH inductor, 85 percent of the total inductive energy of the circuit remained after commutation.

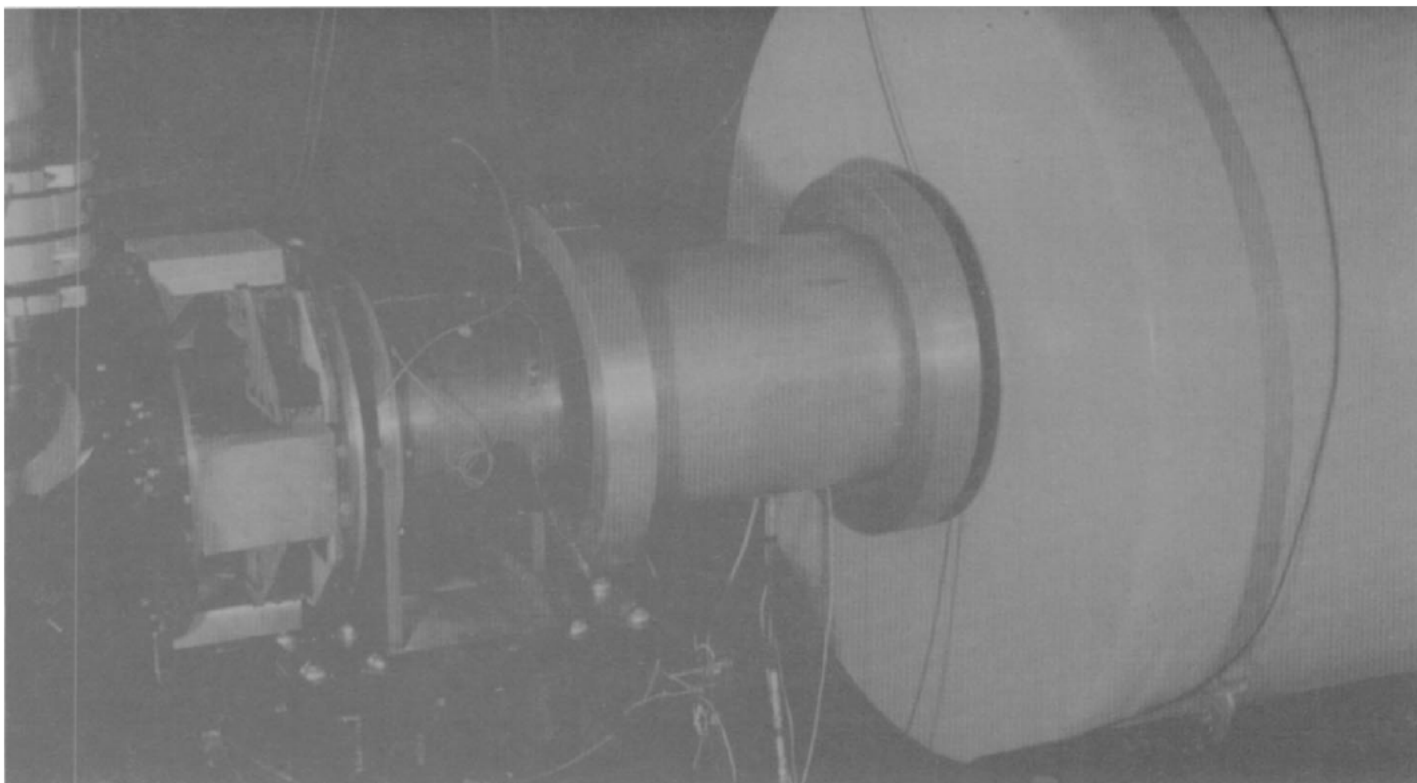


Figure 3. Explosive switch and mechanical switch mounted on the cryogenic inductor for testing

Explosive Closing Switch

Figure 4 illustrates an explosively-operated version of the magnetically-operated switch of Boissady and Rioux-Damidaou.¹⁰ The metal ring is projected into the tapered gap between the coaxial electrodes by a ring of detonating cord. The detonating cord and the metal ring are carried in a polyethylene insulator as shown. Although the switch must be reloaded for each shot, all of the components are reusable except the metal ring and the polyethylene insulator.

The detonating cord is detonated at diametrically opposite points. The detonation wave proceeds in both directions from each detonation point at a velocity of 8 km/s. Although there is a one microsecond delay from firing until the detonation is complete, this delay has no adverse effect on switch operation. The explosive charge is small (1 g) and the detonation takes place inside the switch, allowing the switch to be safely used indoors.

The explosive closing switch shares a number of advantages with its magnetic predecessor. Switch closure results from direct metal-to-metal contact, eliminating the voltage drop associated with arc-initiated switches. The magnetic pressure of the switch current acts to assist the closure, as does the wedging action of the ring in the tapered gap. The coaxial geometry results in high mechanical strength, low inductance, and is convenient for coaxial buses or coaxial cabling.

We have developed an explosive version of the magnetic switch for several reasons. The use of explosives allows the use of more massive metal rings, increasing the thermal capacity of the switch. The switch is self-contained, requiring only a low-energy external firing circuit, the same firing circuit serves switches of all sizes. The explosive closing switch is simple and compact, and lends itself to scaling to larger sizes.

The switch is presently in use to crowbar railguns as the projectile exits the muzzle. With a 90-g, 12-cm diameter copper ring and 3.2-g/m detonating cord, the delay between the detonating pulse and switch closure is 60 μ s, the jitter is 5 μ s. The switch has successfully crowbarred megampere currents.

We foresee the use of the explosive closing switch in heavy-duty applications such as crowbarbing homopolar generators and isolating parallel homopolar-charged inductors.

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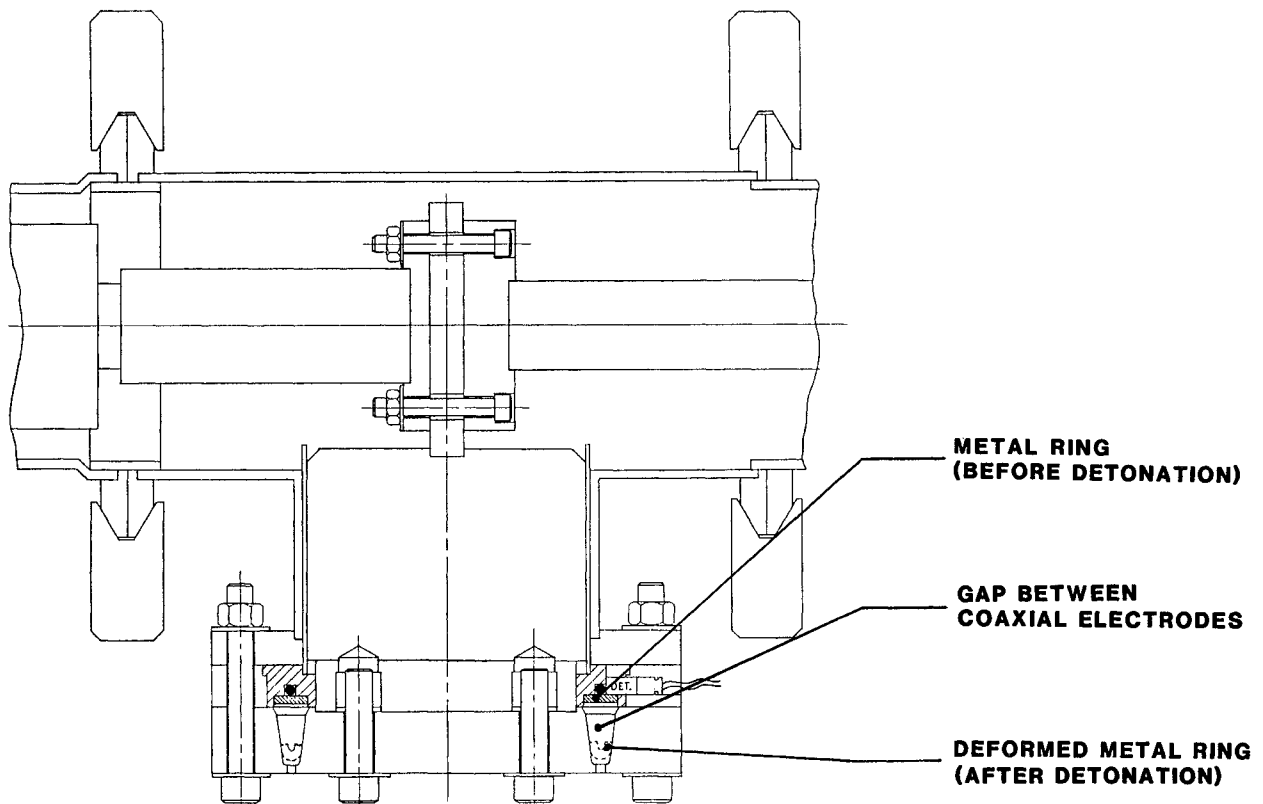


Figure 4. Illustration of closing switch

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